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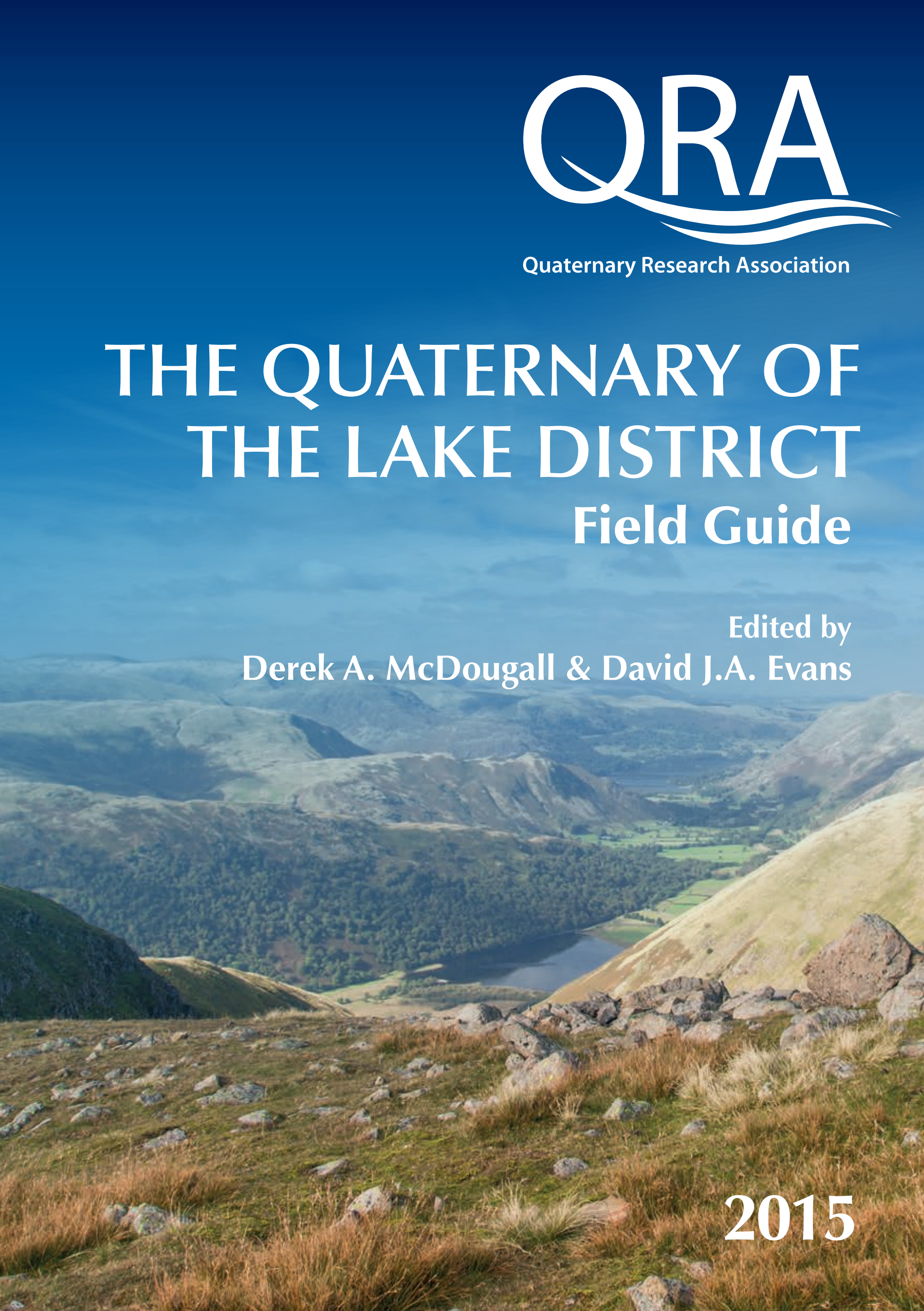

THE QUATERNARY OF THE LAKE DISTRICT

Field Guide

Edited by

Derek A. McDougall & David J.A. Evans

2015

Cover Photograph: Stony Cove Pike, looking towards Brothers Water and Ullswater (D. McDougall).

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Wasdale Head

D.J.A. Evans, V.H. Brown, D.H. Roberts, J.B. Innes, H.L. Bickerdike, A. Vieli and P. Wilson

Introduction

The area of Wasdale Head and Wastwater represents one of the finest examples of a glacially eroded mountain landscape in Britain (Figure 14.1). The overdeepend trough hosting Wastwater lake has been glacially eroded to produce a 79 m deep rock basin (Ramsbottom 1976), a process effected by glacier ice emanating from icefields that have accumulated on the surrounding mountainous terrain on numerous occasions during the Quaternary. The alpine style of glacial topography, comprising troughs, trough head valleys and cirques, is the product of average glacial conditions (Porter 1989; McCarroll 2006) characterized by mountain icefields occupying the upland terrain for most of time during cold stages (Figure 14.1a, b). Since deglaciation a variety of paraglacial slope landforms have developed (Wilson 2005), the most celebrated of which are the Wastwater Screes (Figure 14.1c; Andrews 1961; Huddart 2002).

Wasdale Head comprises two trough end valleys, Mosedale and Lingmell Beck, which drain the steep slopes of the mountains Great Gable, Kirk Fell, Pillar, Red Pike and Yewbarrow and the western bastions of the Scafell range. Although the heads of both valleys link with the relatively low cols of Black Sail Pass and Sty Head, they also ascend into and are surrounded by well-developed cirque basins. The head of Mosedale is defined by a large cirque (Black Comb) with a poorly defined floor and is almost contiguous with another subdued cirque in Gatherstone Head on the watershed between Mosedale and Ennerdale (Black Sail Pass). Its western slopes ascend into the three cirques of Wistow Crags/Red Pike, Black Beck and Black Crag (Evans and Cox 1995; I.S. Evans 2003). Lingmell Beck lies below the cirque complex developed on the northern flanks of Great End, Broad Crag and Scafell Pike (Dropping Crag, Round How and Broad Crag cirques; I.S. Evans 2003). The accumulation of ice in these upland basins during the Younger Dryas resulted in the advance of extended cirque glaciers into the trough heads of Mosedale and Lingmell as well Lingmell Gill (Hollow Stones

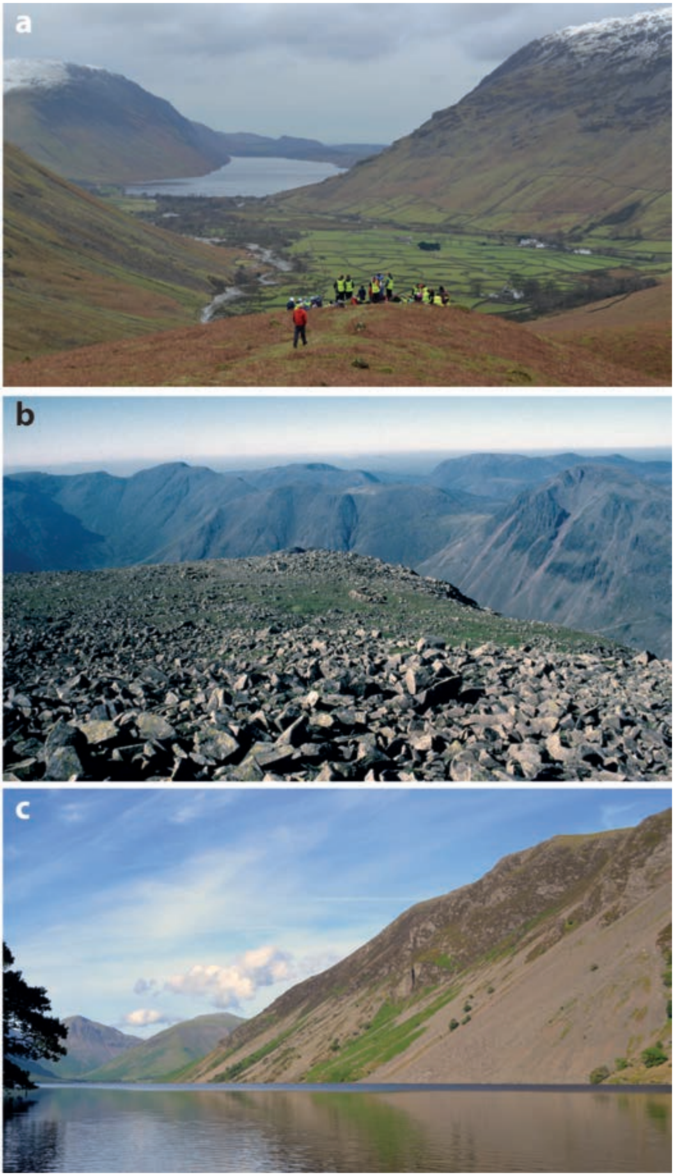


Figure 14.1. General views of the glacial landscape of Wastwater and Wasdale Head (DJA Evans): a) view westwards from the lateral moraines of Lingmell Beck, showing the overdeepened trough of Wastwater, the alluvial fan delta of Wasdale Head and the Wastwater Screes; b) view across the blockfield on the summit of Scafell Pike looking across Wasdale Head to Great Gable (right), Kirk Fell (centre) and Pillar/Red Pike encircling Mosedale (left); c) view from the west end of Wastwater, showing Wastwater Screes, Lingmell and Great Gable.

cirque; I.S. Evans 2003) on the western slopes of Lingmell and Scafell Pike but the exact extent of the snouts has been the subject of some debate, largely due to a paucity of dating control. We here present the various lines of landform evidence for former cirque and valley glaciation around Wasdale Head and differentiate certain non-glacial features that could be mis-interpreted in palaeoglaciological reconstructions and which have contributed to the evolution of this mountain landscape during postglacial time.

Mosedale depositional landforms

Mosedale is a 2.5-km-long, SE-facing valley surrounded by some of the highest terrain in the Lake District, indicated by Kirk Fell at 802 m OD, and bounded by the cirques of Black Comb, Gatherstone Head, Wistow Crags/Red Pike, Black Beck and Black Crag (Evans and Cox 1995; I.S. Evans 2003). Although the valley sides of Mosedale are largely blanketed by paraglacial deposits and recent talus and debris flow-fed fans, the floor of the lower valley contains numerous, substantial debris ridges and mounds, most of which have a glacial origin (Figure 14.2). Some are less diagnostic of glacial deposition due to their plan forms and locations. Large drift benches and linear ridges are best developed on the lower slopes of Kirk Fell where mapping has revealed a shallow down-valley dip in summit crests and in some cases, arcuate across-valley trends (Figure 14.2a, b; Brown et al. 2011, 2013). The morphology and inset, en echelon pattern of these ridges are typical of latero-frontal moraine construction by a valley glacier in Mosedale at elevations below 260 m OD (Figure 14.2d). The outermost moraine ridges on the southeastern flank of Kirk Fell are locally coalescent with similar features that document glacier marginal recession into Lingmell Beck (Figure 14.2, d). These moraines are of a similar age to those that lie on the lower slopes of Yewbarrow, directly above Wasdale Head Inn, and the western spur of Lingmell, documenting the expansion of Mosedale and Lingmell Beck ice to the head of Wastwater.

Amongst the latero-frontal moraines on the floor of Mosedale are a number of non-orientated hummocks and circular ramparted features, not all of which are unequivocally glacial in origin. One large, near circular hummock lies directly below the bedrock cliffs and pinnacles of Stirrup Crag on the northern flanks of Yewbarrow (Figures 14.2a, b, d and 14.3). Although it has been dissected by postglacial stream incision, it appears to have once been continuous with a boulder fan on the lower slopes of Yewbarrow. Its isolated nature, apparent former connection to a valley side fan, and lack of alignment with any of the latero-frontal moraines suggests that it is a rock avalanche cone, deposited

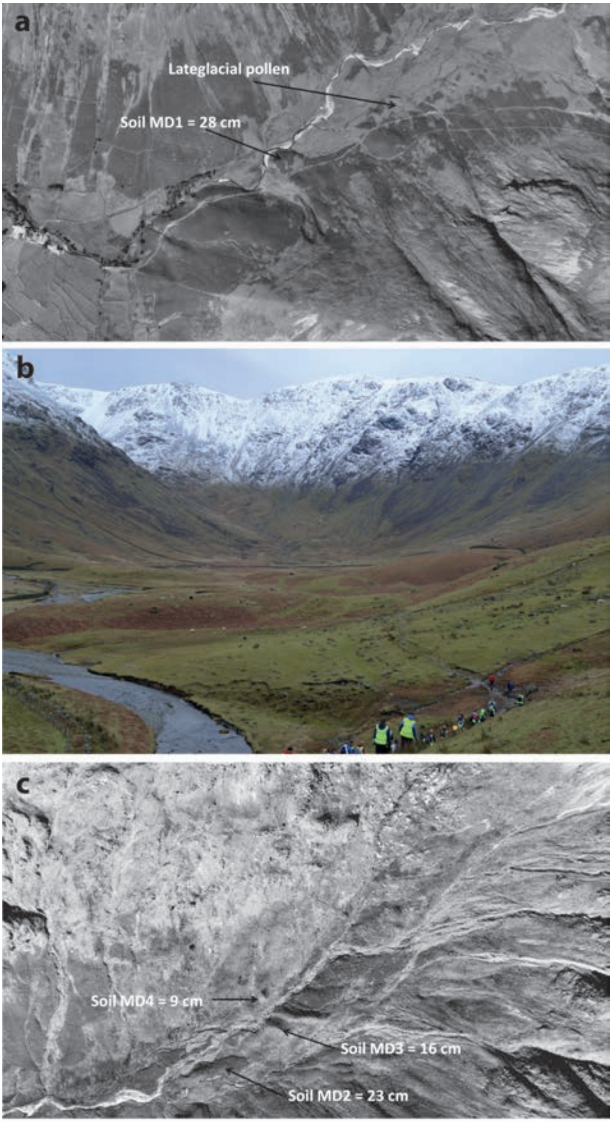
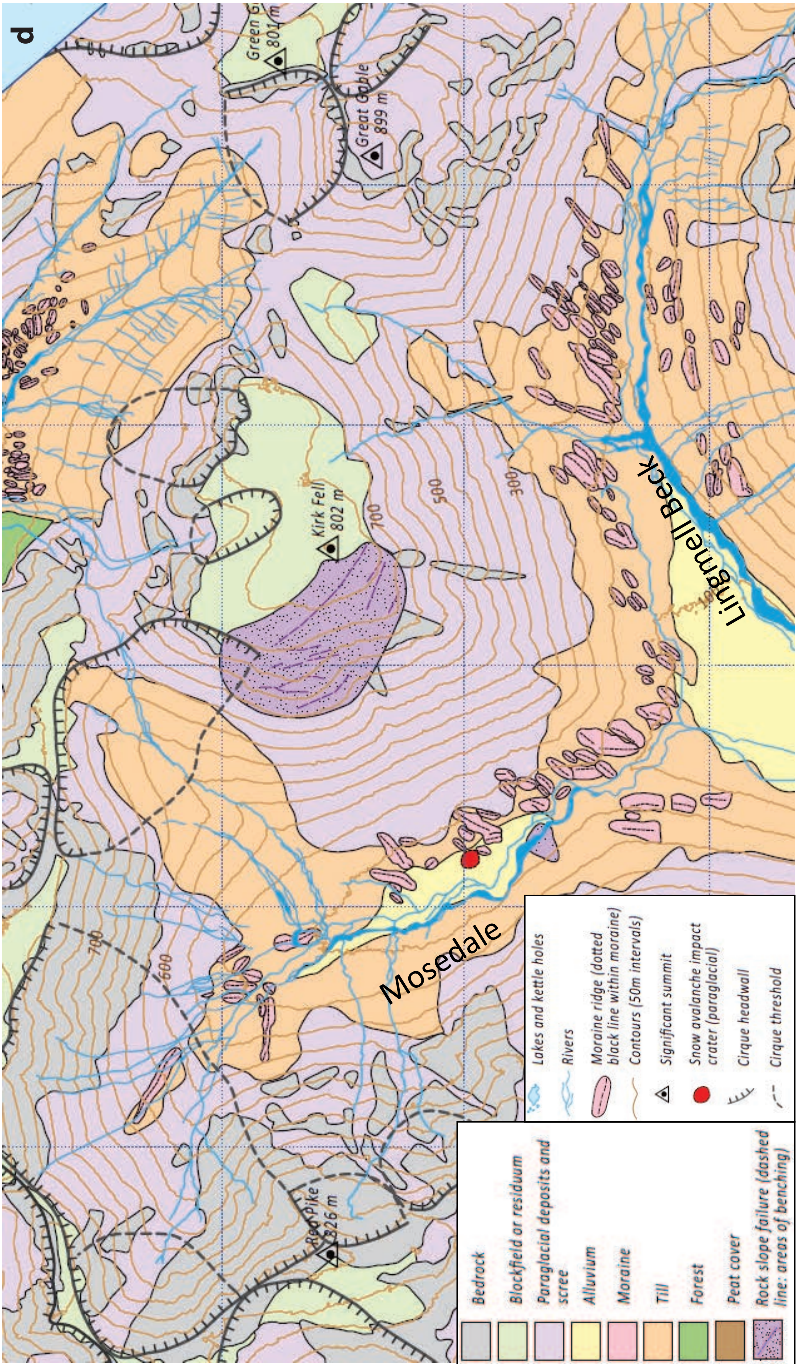


Figure 14.2. Aerial photograph and geomorphology map extracts of depositional landforms in Mosedale: a) part of OS aerial photograph 72.342.274 (crown copyright) showing the drift ridges and hummocks on the floor of the main valley of Mosedale; b) view into Mosedale, showing the large depositional ridges and mounds on the main valley floor; c) part of OS aerial photograph 72.342.220 (crown copyright), showing the dual latero-frontal moraine ridges in Black Comb, interpreted as the Younger Dryas limit; d) (opposite) part of the surficial geology and geomorphology map of the SW Lake District, showing the landforms of Mosedale and Lingmell Beck (from Brown et al. 2011).



d
Great Gable
899 m
Kirk Fell
802 m
700
500
300
Lingmell Beck
Mosedale
700
600
Red Pike
826 m
Lakes and kettle holes
Rivers
Moraine ridge (dotted black line within moraine)
Contours (50m intervals)
Significant summit
Snow avalanche impact crater (paraglacial)
Cirque headwall
Cirque threshold
Bedrock
Blockfield or residuum
Paraglacial deposits and scree
Alluvium
Moraine
Till
Forest
Peat cover
Rock slope failure (dashed line: areas of benching)

Figure 14.3. View across the circular debris mound, interpreted as a potential rock avalanche deposit, lying below Stirrup Crag on Yewbarrow. The continuation of this deposit onto the slopes below Stirrup Crag as a boulder fan is outlined by a broken line (DJA Evans).

by a RSF from Stirrup Crag, rather than part of a hummocky moraine spread. Post-depositional stream incision has exploited the lower topography between the fan and the more substantial mound of the run out deposits. Another remarkable feature is a circular steep-sided rampart, encircling a peat-filled central depression and lying directly below a debris flow-fed fan emanating from the largest of the bedrock gullies incised into the western summit slopes of Kirk Fell (Figures 14.2a, d and 14.4a). The fan has entirely covered the lateral moraine ridges on this part of the mountainside and its base links directly to the circular, ramparted depression. Unlike the fan base, the circular rampart appears to be composed predominantly of angular boulders. This feature has all the characteristics of snow avalanche impact pits reported from modern dynamic mountain environments such as the Canadian Rocky Mountains (Figure 14.4b; cf. Smith et al., 1994). Such landforms are created by snow/slush avalanching during periods of significant snow accumulation in mountainside gullies and niches and document the bypassing of talus cones and delivery of debris directly to the valley floor (Luckman 1977; Corner, 1980; Fitzharris and Owens, 1984; Smith et al., 1994). Large boulders run out beyond the accumulating snow/slush avalanche deposit at the base of the talus and hence are concentrated in a circular ridge once the snow melts out.

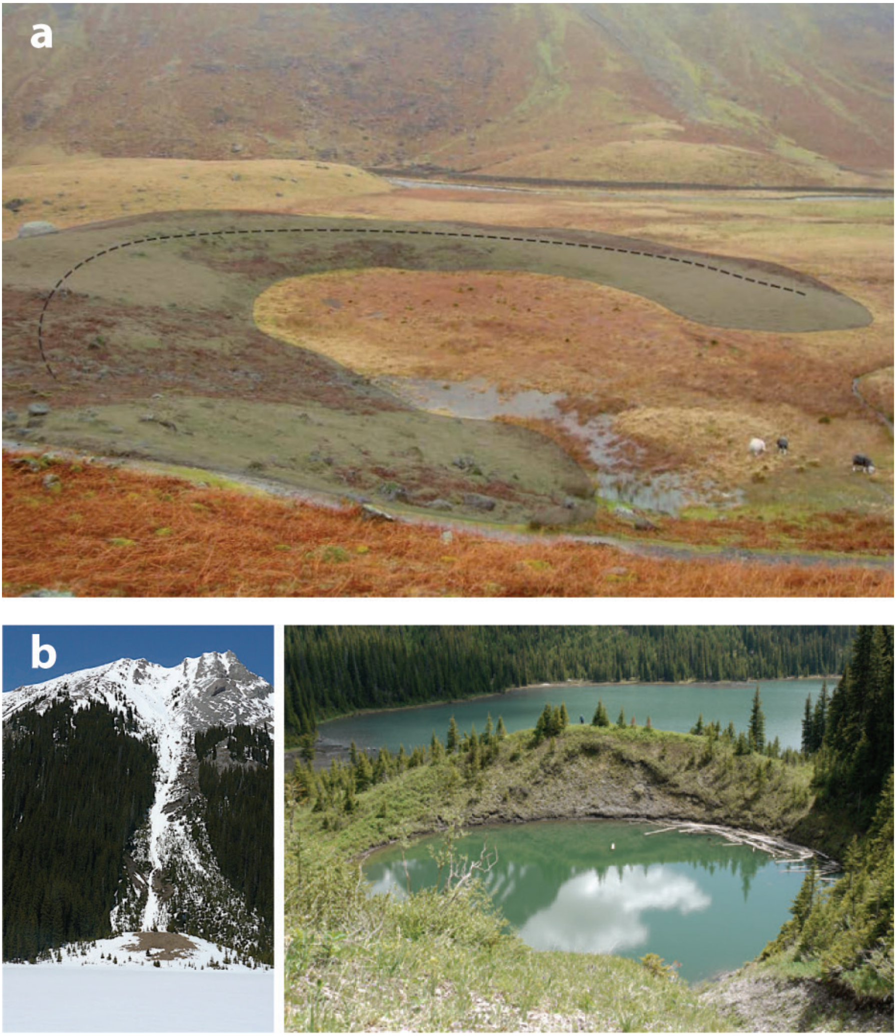


Figure 14.4. The Mosedale snow avalanche impact pit: a) view across the feature from the slopes of Kirk Fell with circular ridge and ridge crest highlighted (from Brown et al. 2011); b) modern analogue at Burstall Lake, Kananaskis in the Canadian Rock Mountains (G. Daffern).

Although smaller in volume than the debris mounds and moraines in the main valley, the depositional ridges of Black Combe are nonetheless sharply defined and clearly resemble latero-frontal moraine arcs which descend to 178 m asl (Figures 14.2c and 14.5). The most prominent features are two closely spaced latero-frontal moraines (Figure 14.5) the “freshness” of which was used by

Figure 14.5. View looking south along Mosedale from Black Comb with the dual ridge latero-frontal moraine loops in the middle ground, with groups of Durham students for scale on the inner ridge (DJA Evans).

Sissons (1980) to propose them as the limit of the Younger Dryas glacier in Black Combe.

Lingmell Beck depositional landforms

Lingmell Beck is a predominantly westerly-facing valley surrounded by the steep slopes of Scafell Pike (978 m OD) to the south, Great End (910 m OD) to the east, and Great Gable (899 m OD) and Kirk Fell (802 m OD) to the north. As the valley is narrower than Mosedale, the substantial debris mounds in Lingmell Beck occupy the valley walls up to 350 m OD rather than its floor (Brown et al. 2011). The mounds are linear features and dip gently down valley towards Wasdale Head in an inset or en echelon pattern, forming arcuate bands that can be interpreted only as latero-frontal moraine loops (Figures 14.2d and 14.6). A significant difference is apparent in the moraine volume between the north and south valley sides, with only fragmentary, discontinuous and low amplitude ridge chains occurring on the south valley wall and higher relief, continuous and more voluminous offlapping ridges being characteristic of the north valley wall. Indeed, the north wall moraines are thick enough to completely blanket the

Figure 14.6. Aerial photograph extract (OS 72.342.274, crown copyright), showing the glacial depositional landforms of Lingmell Beck.

Figure 14.7. Exposure through paraglacial slope deposits and underlying lateral moraine ridges on the southern slopes of Kirk Fell (DJA Evans).

bedrock topography, whereas the south valley wall contains numerous outcrops of bedrock visible through the predominantly thin and patchy drift (Figures 14.6). Paraglacial slope deposits are also more substantial on the north valley wall, evident in the stratigraphic exposures afforded by recent fluvial and debris flow scars (Figure 14.7). These observations suggest that there is a significant within-valley asymmetry of moraine development (Matthews and Petch 1982; Benn 1989), likely controlled by the extensive, oversteepened bedrock exposures on the south flanks of Great Gable, well-illustrated by the popular rock climbing haunts of Great Napes (Figure 14.1b).

Lingmell Gill depositional landforms

Unlike the deeper and wider lower profile valley forms of Mosedale and Lingmell Beck, the mountainside valley of Lingmell Gill descends steeply over a distance of 2.5 km from the mid slopes of Lingmell and Scafell Pike. Closely-spaced drift mounds form an almost complete cover on the southern half of the valley floor between the Hollow Stones cirque lip beneath Scafell Pike and the 450 m OD contour half way down Lingmell Gill (Figure 14.8). The down-valley dip of these linear ridges and their arcuate, inset or en echelon plan forms are indicative of a latero-frontal moraine origin. Similar landforms occur in the lower reaches of Lingmell Gill at its junction with the main valley of Wasdale Head between

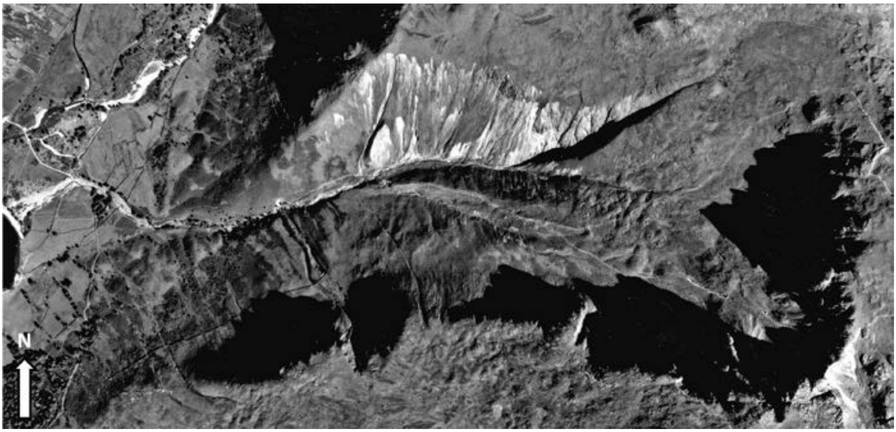
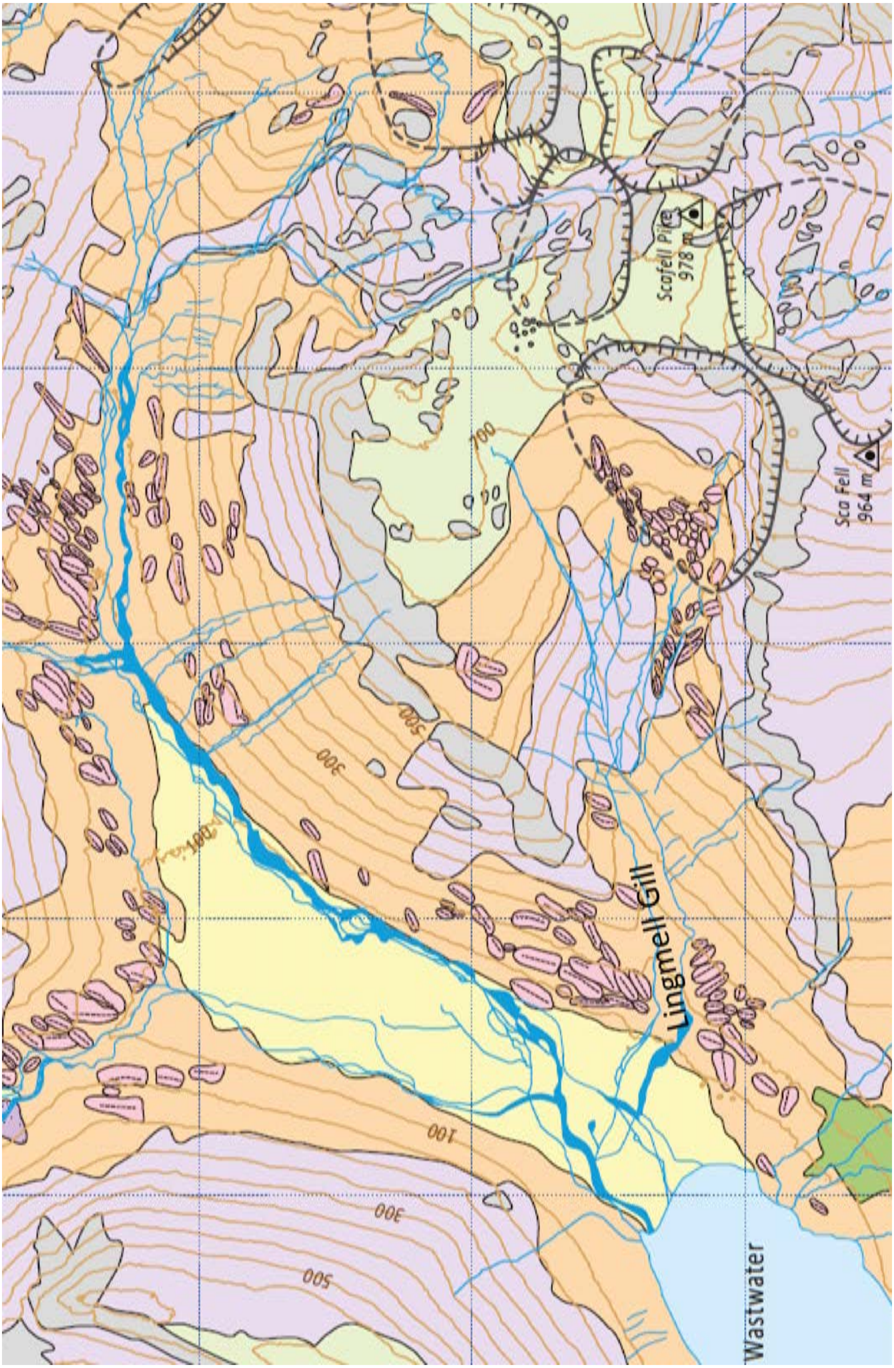


Figure 14.8. Aerial photograph and geomorphology map extracts of depositional landforms in Lingmell Gill: a) (above) part of OS aerial photograph 72.342.273 (crown copyright) showing the drift ridges and hummocks on the south floor of the valley as well as the asymmetrical distribution of the cirque south backwall and lateral margin; b) (opposite) part of the surficial geology and geomorphology map of the SW Lake District, showing the landforms of Lingmell Gill in relation to those of Wasdale Head and Lingmell Beck (from Brown et al. 2011).


Scafell Pike
978 m
Sca Fell
964 m
Lingmell Gill
Wastwater
700
500
300
100

150–300 m OD, but these features are more subdued and clearly form a separate assemblage to those at higher altitude. This separation of moraines into two discrete assemblages based upon prominence or "freshness" was employed by Sissons (1980) to propose a small cirque glacier in upper Lingmell Gill. The occurrence of morainic mounds almost exclusively in the southern half of the valley is an indication of within-valley moraine asymmetry (Matthews and Petch 1982; Benn 1989) and clearly relates to the more extensive and higher backwall and sidewall areas on the southern margins of the cirque (Figure 14.8a) which would have delivered large volumes of extraglacial debris during ice occupancy.

Rock slope failures around Wasdale Head

Two substantial rock slope failures (RSFs) occur on the mountain summits surrounding Wasdale Head, one on the western margin of Kirk Fell (Figure 14.9) and the other on the eastern ridge of Illgill Head, above Wastwater Screes (Figure 14.10; Wilson 2005). The Kirk Fell feature, the extent of which is mapped in Figure 14.2d, was first identified by Ward (1873b) as an area of linear depressions crossing each other at various angles and covers an area of 0.35 km^2. The failure zone comprises an area of antiscarps and benches which indicate a large failure transitional between incipient and arrested translational sliding. Previous work

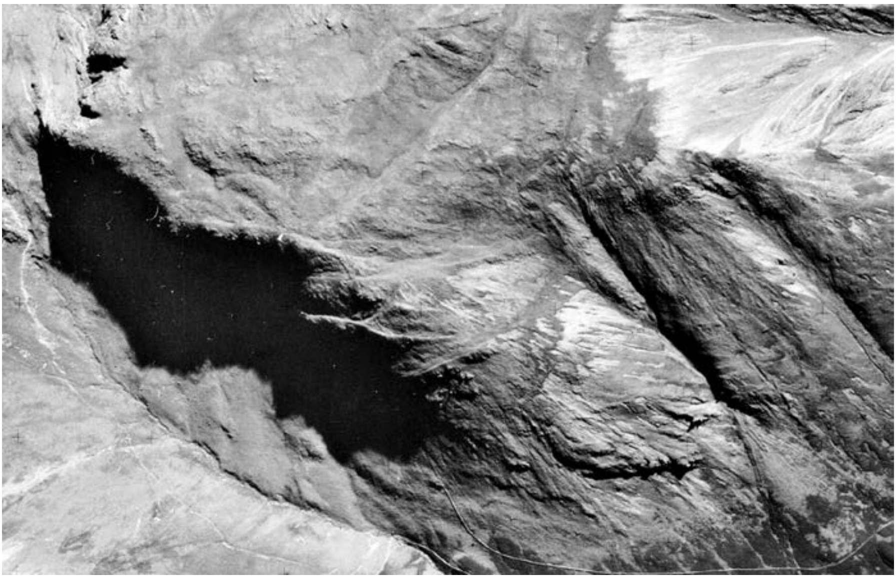


Figure 14.9. Aerial photograph extract (OS 72.342.274, crown copyright), showing the RSF on the SW margin of the summit of Kirk Fell.

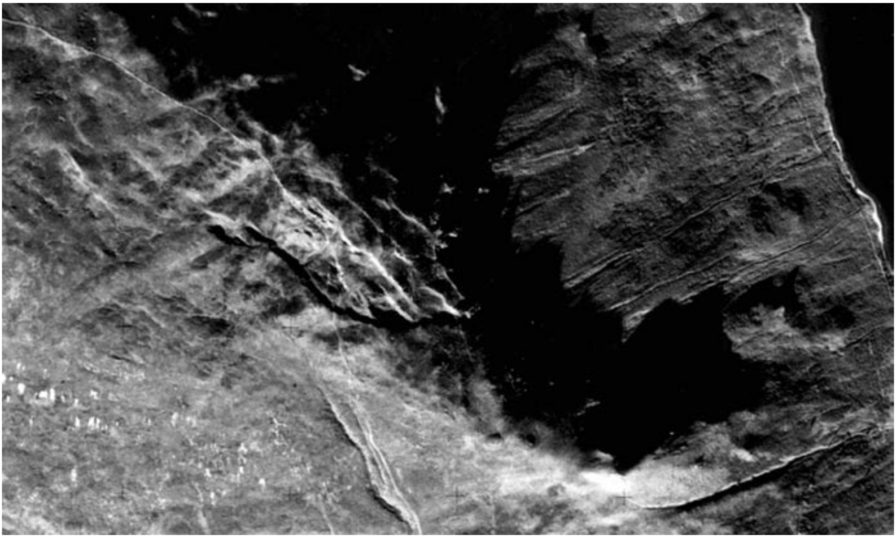


Figure 14.10. Aerial photograph extract (OS 72.342.222, crown copyright), showing the RSF on the eastern end of the summit of Illgill Head, above Wastwater Screes.

on such features (Jarman and Ballantyne 2002) has proposed either long term gravitational slope deformation by rock mass creep or shearing of adjacent rock units whereby the downslope unit moves upwards by reverse faulting.

The Illgill head RSF (Figure 14.10) is the largest (0.05 km^2) of four that lie along the ridge above the Wastwater Screes (failure D of Wilson 2005). First identified by Ward (1873b) as an area of fissures, tumbled craggy rocks, subsidence and a trough fault, the failure zone also comprises megablocks and sinuous ridges which have produced a hummocky topography with amplitudes up to 10 m. Although site D displays a greater degree of disturbance than the other three summit RSFs, the debris remains in the failure scar and hence it is an arrested translational slide. Nonetheless, the Illgill Head RSFs clearly have contributed significantly to the accumulation of the Wastwater Screes and hence this famous slope deposit is likely predominantly of a paraglacial origin despite evidence of historical rock avalanche activity. The corollary is that the bulk of the screes had accumulated by the end of the Lateglacial.

Chronology of events at Wasdale Head

Previous reconstructions of palaeoglaciation around the southwest Lake District have been based upon very few age determinations. Sissons (1980) proposed that the Younger Dryas glaciation limit in the area was recorded by the dual

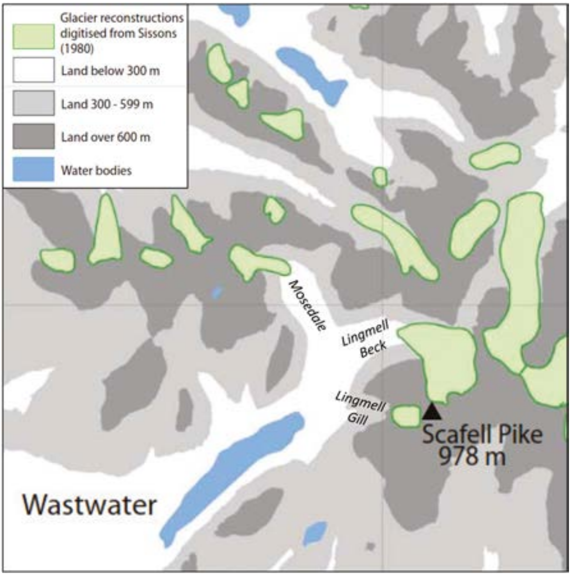


Figure 14.11. The extent and distribution of Younger Dryas glaciers around Wasdale Head and adjacent areas according to Sissons (1980).

latero-frontal moraines in Black Comb, Mosedale, the smaller but relatively sharper crested moraines in the middle reaches of Lingmell Beck and the higher altitude assemblage of densely spaced moraines in upper Lingmell Gill based upon topographic "freshness" (Figure 14.11).

The restricted nature of cirque based glaciers proposed by Sissons (1980) appeared to be supported by an initial absolute chronology in the area provided by the occurrence of an undisturbed Lateglacial biostratigraphic sequence at Sty Head Tarn (Pennington 1978; Pennington 1996). The location of this site at 436 m OD is problematic if a more extensive, plateau icefield style of Younger Dryas glaciation is proposed (e.g. Brown et al. 2013). Such a reconstruction accounts for the linkage of a Lingmell Beck glacier snout with more extensive ice over Sty Head, also required in order to deliver a valley glacier to Borrowdale on the other side of the watershed; the reasoning behind this palaeoglaciological reconstruction is discussed in the next section. The inherent problems with the Sty Head site have been summarized by Brown et al. (2011). The stratigraphic evidence reported from the site by Pennington (1978) comprises two clay layers separated by a slightly organic silt, prompting the interpretation that the lake basin contains a record of Younger Dryas minerogenic inwash over Lateglacial Interstadial deposits, but the sequence has never been radiocarbon dated. Some disturbance in the uppermost section of the core is believed to be associated

Figure 14.12. Previously unmapped moraines of Sty Head: a) Oblique Google Earth image of Sty Head showing the position of a latero-frontal moraine deposited by a glacier lobe emanating from Great End. Black broken line is drawn along the outer edge of the moraine ridge; b) Vertical Google Earth image showing the moraines that converge on Sty Head from Great End and Aaron Slack.

with lake ice melting at the close of the Loch Lomond Stadial. The potential Lateglacial deposits comprise 18 cm of organic silt recording an increase in *Betula*, *Cyperaceae*, *Juniperus* and *Empetrum* during. An abrupt transition into the Younger Dryas clay is accompanied by a reduction in *Betula*, *Cyperaceae*, *Juniperus* and *Empetrum* and an increase in *Artemsia*. The biostratigraphy of the Sty Head Tarn core therefore appears to provide a robust high resolution record of the Lateglacial to early Holocene environment at this high elevation site and thereby constitutes a significant challenge to palaeoglaciological reconstructions of ice passing through the watershed into the surrounding valleys. If the evidence is accepted as an indication that the area was ice free during the Younger Dryas, the alpine style of glaciation proposed by Sissons (1980) is viable. However, a plateau icefield style of glaciation is not necessarily incompatible with the biostratigraphic evidence either, as Sty Head pass is only marginal to reconstructions of plateau icefield ice cover (see below), which indicate only very thin ice/névé or that ice was not present over Styhead Tarn for the full duration of the Younger Dryas (Brown et al. 2013). Significantly, we have identified a moraine ridge on the southeastern shore of the tarn (Figure 14.12), not previously mapped, which is compatible with a glacier lobe emanating from the cirque basins on the north side of Great End (Sprinkling Tarn and/or Spout Head) and marks at least a recessional position of glacier ice entering the Borrowdale drainage basin from the Scafell massif.

Cosmogenic exposure ages are now being obtained from a variety of sites around the Lake District in relation to the former extent of Younger Dryas glacier cover. An age of 17.3 ka BP from Lingmell Col has been interpreted by Ballantyne et al. (2009) as evidence for ice-free conditions during the Younger Dryas, although these ages are also compatible with a plateau icefield glaciation style which indicates only a cover of thin and likely cold based ice during the stadial (see below; Brown et al. 2013). Deglacial ages of 14.2 and 13.5 ka BP have been reported from a roche moutonneé on the south slopes of Middle Fell, on the north central shore of Wastwater, by McCarroll et al. (2010) and have been re-calibrated to 16.2 and 14.3 ka BP by Wilson et al. (2013) using production rates proposed by Fabel et al. (2012). These dates indicate a post 14.3 ka BP age for all the moraines at Wasdale Head. Some chronological control has been provided at the northern margins of the former glacier cover in the western Lake District by Wilson et al. (2013). They report cosmogenic ages from moraines within the margins proposed by Sissons (1980) and at the limit of plateau ice proposed by McDougall (2001) (Figure 2.12 in chapter 2), which suggest a pre-Younger Dryas age for the plateau icefield. Inheritance problems are, however, highlighted by Wilson et al. (2013), especially as samples from within the more restricted alpine style limit of Sissons (1980) yielded ages ranging from 13.1-18.1 ka BP (Figure 2.12). The lack of glacial erosion, especially on boulders transported short distances by short-lived mountain glacier lobes, is likely to continue to prove problematic in gaining reliable cosmogenic ages on the moraines of the Lake District.

In order to constrain the age of moraines in Mosedale, we extracted a 375 cm long core from the peat-filled depression in the snow avalanche impact pit (Figure 14.13a). A potential Younger Dryas age for the pit is indicated by numerical modelling (Brown et al. 2013; see below), which reproduces a substantial ice body in the bedrock gulley on the west summit edge of Kirk Fell, which would likely have fed large volumes of material to the debris fan immediately above the pit. However, the lithostratigraphy and pollen record extracted from the base of the peat-filled depression in the former avalanche impact pool reveals a clear Lateglacial stratigraphic and vegetation signal (Figure 14.13). The basal 25 cm of the core revealed a vertical sequence of grey-brown silt/clay, overlain by blue clay and then grey-green clay/gyttja, indicative of an increasingly organic pond infill. This was then capped by a 7 cm thick unit of grey sand/silt recording renewed inorganic inwash, passing upwards into 10 cm of brown gyttja and then more than 3 m of peat. Initial interpretations (Figure 14.13a) were that this sequence recorded LGM deglaciation, the Lateglacial Interstadial, the Younger Dryas and the Holocene. Pollen counts on the stratigraphy between 365 - 338 cm facilitated the identification of six pollen zones (M1-M6, Figure 14.13b). A twin *Artemisia* peak (M2 and M4) is likely to record the Older Dryas cold spell at c. 12ka BP and the Younger Dryas. Other tundra type herbs like *Plantago maritima* and *Ranunculus* also increase in zone M3 to M4, supporting a Younger Dryas age for zone M4. This identification of the YD cold phase is supported by the major reduction in the Juniperus curve during zone M4, complementing the *Artemisia* peak. This biostratigraphy suggests a post-Dimlington Stadial age for the pit and demonstrates that the moraine ridges further down valley must also date to LGM deglaciation, supporting Sissons' (1980) proposal that the Younger Dryas glacier in Mosedale is defined by the dual latero-frontal moraine ridges in the lower reaches of Black Comb.

Further relative age dating on the Mosedale moraines and slope deposits is provided by a soil chronosequence in the valley. Soil B horizon depths on the Black Comb latero-frontal moraines (Younger Dryas limit of Sissons 1980) are 16 cm (MD3; outer ridge) and 9 cm (MD4; inner ridge; Figure 14.2c). These contrast with a B horizon depths of 23 cm and 28 cm for the lower valley floor moraines in Mosedale (MD2 and MD1 respectively; Figure 14.2a), indicating a a

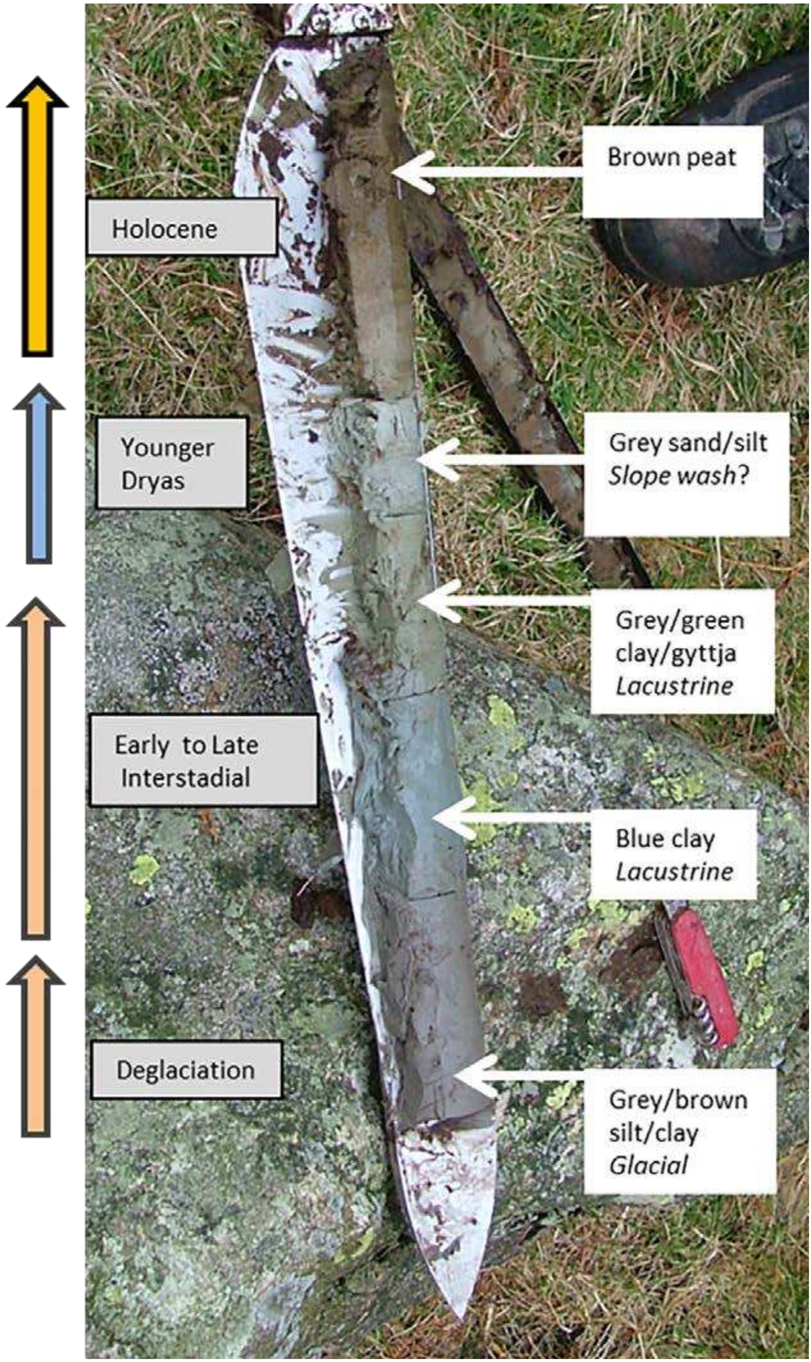
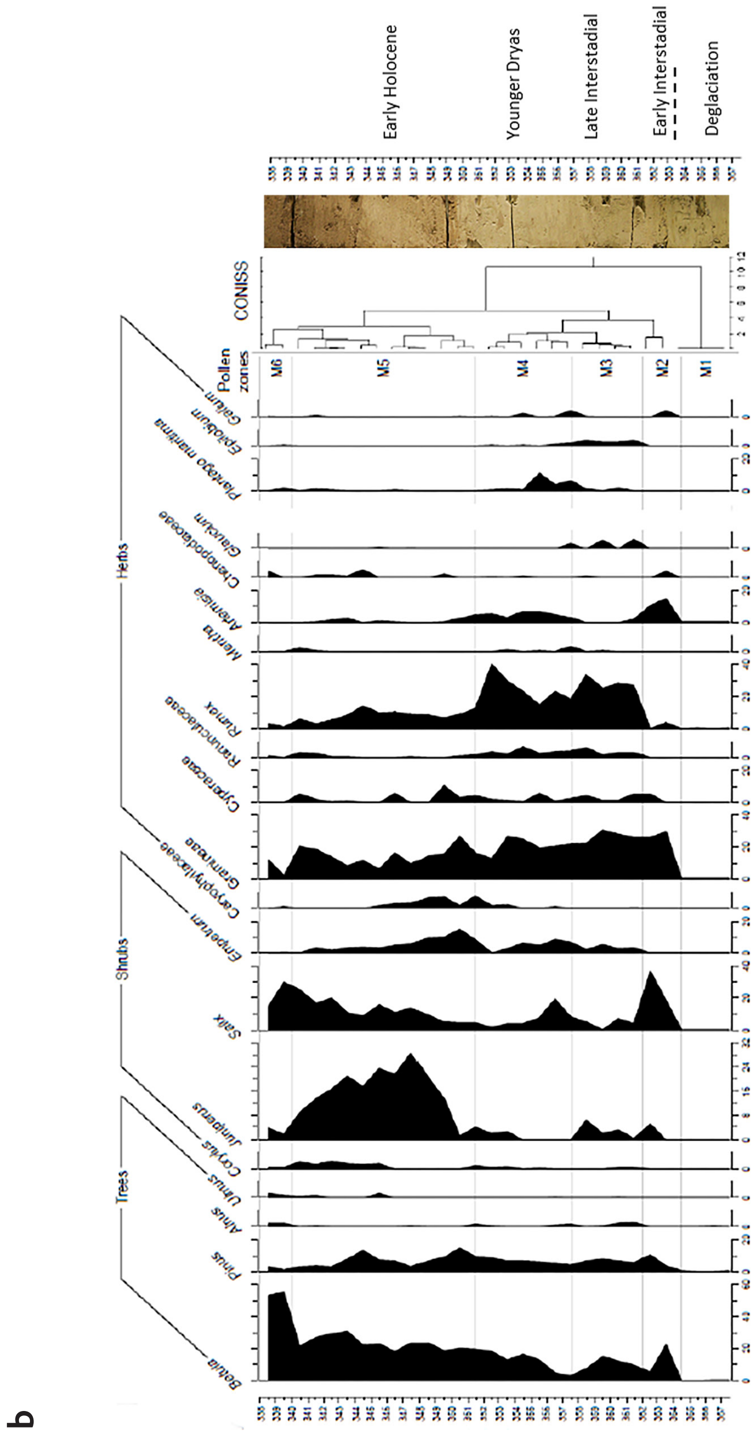


Figure 14.13. Stratigraphy (a) and (opposite) pollen record (b) from the snow avalanche impact pit in Mosedale.


b
Early Holocene
Younger Dryas
Late Interstadial
Early Interstadial
Deglaciation
CONISS
Pollen zones
M6
M5
M4
M3
M2
M1
Trees
Shrubs
Herbs
Betula
Pinus
Alnus
Ulmus
Corylus
Juniperus
Salix
Empetrum
Caryophyllaceae
Gramineae
Cyperaceae
Ranunculaceae
Rumex
Mentha
Artemisia
Chenopodiaceae
Glaucium
Plantago maritima
Epilobium
Galium

significant difference in age between the Mosedale valley floor debris mounds/ moraines and the Black Combe moraines and displaying an increase in soil depth with age since moraine abandonment. As a Younger Dryas age for the Black Combe moraines is strongly supported by the discovery of a Lateglacial site in the snow avalanche impact pit, the 9 – 16 cm soil depths can be employed as a relative age dating control on other moraine sequences around the Lake District. Hence the age-constrained morphostratigraphy of Mosedale will prove to be crucial to the establishment of a soil chronosequence dating framework for Younger Dryas glacier limits in the region.

Palaeoglaciological reconstructions for Wasdale Head

The paucity of dating controls on the glacial landforms around Wasdale Head, not unlike all other areas of the Lake District, hamper the identification of a Younger Dryas glaciation limit. The application of a plateau icefield style of palaeoglaciological reconstruction to areas of upland Britain, initially by Rea et al. (1998) and McDougall (2001) and more recently by Brown et al. (2011, 2013), Boston (2012), McDougall (2013), Pearce et al. (2014), using glaciological principles informed by observations on modern mountain icefields (Rea and Evans 2007), has necessitated a more expansive glacier ice cover than the cirque or alpine style of glaciation proposed by Manley (1959) and Sissons (1980). This approach demands more realistic glacier morphologies/hypsometries with respect to ratios of accumulation and ablation and moreover can be used to assess the viability of a Younger Dryas age independently of morphological "freshness" providing some chronological control is available somewhere around the margins of the plateau icefield; of the twelve Lateglacial sites identified by Sissons (1980), only that of Sty Head is difficult to reconcile with a plateau icefield palaeoglaciology and this may be a site that was located at the very margins of an ice dispersal centre (see rationale above). Additionally, some independent verification of ice extent can be determined by using numerical modelling constrained by palaeoclimate data (Brown et al. 2013).

Two palaeoglaciological reconstructions are presented here for the Wasdale Head area, one based on the traditional (morphostratigraphic; Lukas 2006) approach of moraine "freshness" and palaeo-ELA calculations and another on palaeoclimatically controlled numerical modelling (Brown et al. 2013). The morphostratigraphic approach (Figure 14.14) uses the well-defined moraines of Mosedale, Lingmell Beck and Lingmell Gill to outline glacier margins; the upper limits of the former glaciers were defined using the assumption that glaciers fill their accumulation areas (cirques/valley heads) to an elevation ~30 m below

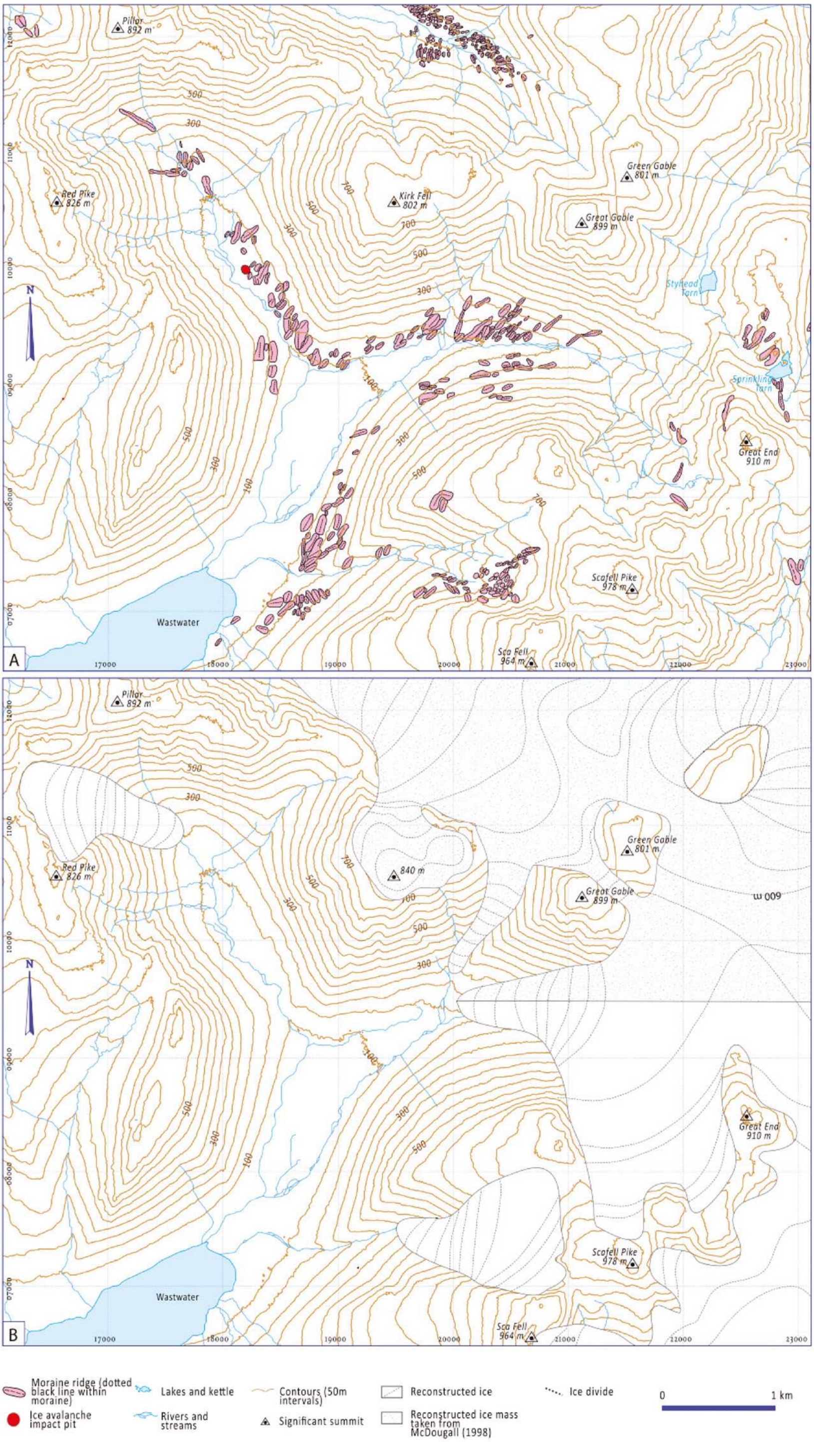


Figure 14.14. The glacial geomorphology (a) and palaeo-glacier reconstruction (b) for Wasdale Head and surrounding fells (from Brown et al. 2013).

the top of the headwall (Wilson and Clark 1998). The Younger Dryas limit is assumed to be represented by the sharpest or freshest moraines, despite the inherent problems of this concept (Wilson 2002). The production of a numerical model allows for an independent assessment of the moraines chosen as the Younger Dryas limit. The glacier surface morphology was reconstructed by producing a series of ice-surface contours at 50 m intervals perpendicular to the orientation of ice flow, as indicated by the geomorphology (Ng et al. 2010). In the accumulation area, convergent flow away from the ice margins and towards the ELA is indicated by contours that are concave down-glacier. In contrast, the contours in the ablation area were drawn to satisfy the divergent ice flow towards the ice margin. The ice-surface contours also take into account the morphology of the glacier bed, most notably in cases where they become much more linear and closely spaced due to bed steepening near the ELA and further apart in areas of shallower bed topography. The ice-surface contours were drawn from the intersection of the contour on the adjacent topography with the edge of the reconstructed glacier, following procedures outlined by Sissons (1980), Ballantyne (1989) and Benn and Ballantyne (2005). The palaeo-ELA reconstructions have been calculated using the Balance Ratio method of Osmaston (2005), cross-checked by the method of Benn and Gemmell (1997).

The glacier reconstructed on the basis of the Black Comb latero-frontal moraines (Figure 14.5) occupied the whole of the Black Comb cirque before narrowing to a smaller and thinner ice tongue, giving a surface area of 0.87 km^2 in contrast to the 0.64 km^2 area calculated by Sissons (1980). The reconstructed ELA using the Balance Ratio method of Osmaston (2005) is 532 m OD (528 m OD using Benn and Gemmell 1997). Our morphostratigraphic reconstruction of the Lingmell Beck glacier is also similar although a little longer in down valley extent to that of Sissons (1980) but the isolation of the glacier from upland icefields as proposed by him is not the most glaciologically plausible. Hence, Brown et al. (2013) proposed to downplay the significance of the apparent Lateglacial Interstadial biostratigraphy at Sty Head and connect the Lingmell Beck glacier to a plateau icefield over the central fells to account for: a) ice flowing northeast from the northern edge of the Scafell range into Borrowdale; b) an ice tongue flowing southeast in Aaron Slack, south of Green Gable (verified by new mapping of moraines on Figure 14.12b); c) the occupation of the cirques on the northwest side of the Scafell massif, whose floor elevations of 445–540 m OD were unlikely to have been ice free during the Younger Dryas; and d) to link up with the plateau icefield of the central fells proposed by McDougall (2001; Figure 3.11 in Chapter 3). Nevertheless the reconstruction in Figure 14.14, when published, represented the maximum ice extent during the Younger Dryas, particularly on Sty Head Pass where ice was likely very thin and non-erosive and/or not present for the whole of the Younger Dryas; indeed the numerical modelling (see below) indicates that the plateau icefield reconstruction produces only a thin ice divide over Sty Head. Our recognition of a moraine at Styhead (Figure 14.12), not included in Figure 14.14, indicates that the Lingmell Beck glacier was likely connected to ice flowing out from the cirques of Great End, supporting the notion that the outlet glaciers were not isolated but were outlet lobes from a plateau icefield. The Lingmell Beck glacier, based on the reconstruction in Figure 14.14, has a palaeo-ELA of 530 m OD using the method of Osmaston (2005) (547 m using Benn and Gemmell (1997). Lingmell Gill glacier is defined by the most prominent latero-frontal moraines in the mid valley area and it occupied the cirque of Hollow Stones below Scafell Crag. This produces a surface area of 1.04 km^2, in contrast to the 0.30 km^2 proposed by Sissons (1980), and a palaeo-ELA of 666 m OD based on the Balance Ratio method of Osmaston (2005; or 605 m OD using Benn and Gemmell 1997). These ELA calculations are respectively 150 m and 70 m higher than those of the Mosedale and Lingmell Beck glaciers, although the recognition of a moraine at Styhead (Figure 14.12) will raise the palaeo-ELA of the Lingmell Beck glacier because of its clear linkage with a large icefield at altitude.

The numerical modelling approach (Figure 14.15) provides perspectives on: i) time-transient and dynamic effects of glacierization, including response times, build-up times and ice flow; ii) regional versus local climate forcing during the Younger Dryas; and iii) alpine versus plateau ice-field styles of glaciation. Details of the model used are provided by Evans et al. (2009) and Brown et al. (2013) and is a standard time-dependent 2-D ice-flow model which calculates ice flow from local ice thickness and surface slope using a Shallow Ice Approximation (SIA; Hutter 1983). The model assumes ice-free conditions prior to the Younger Dryas, an assumption that is consistent with temperature reconstructions (Jones et al. 2002; Bedford et al. 2004), and intrinsically produces mountain or plateau ice fields over high ground because any surface above the ELA experiences accumulation with the exception of slopes steeper than 40°. The ELA is scaled to the temperature record from the GRIP $\delta^{18}O$ ice-core record for the 1300 year period (12.8–11.5 ka BP), encompassing the onset and termination of the Younger Dryas cold phase and which corresponds, in terms of pattern and timing, very closely to the local proxy reconstructions from Haweswater (Jones et al. 2002; Bedford et al. 2004). Importantly, no *a priori* assumptions have been made about moraine age for the model tuning and so multiple moraine positions are possible and indeed the model produces several major advanced positions.

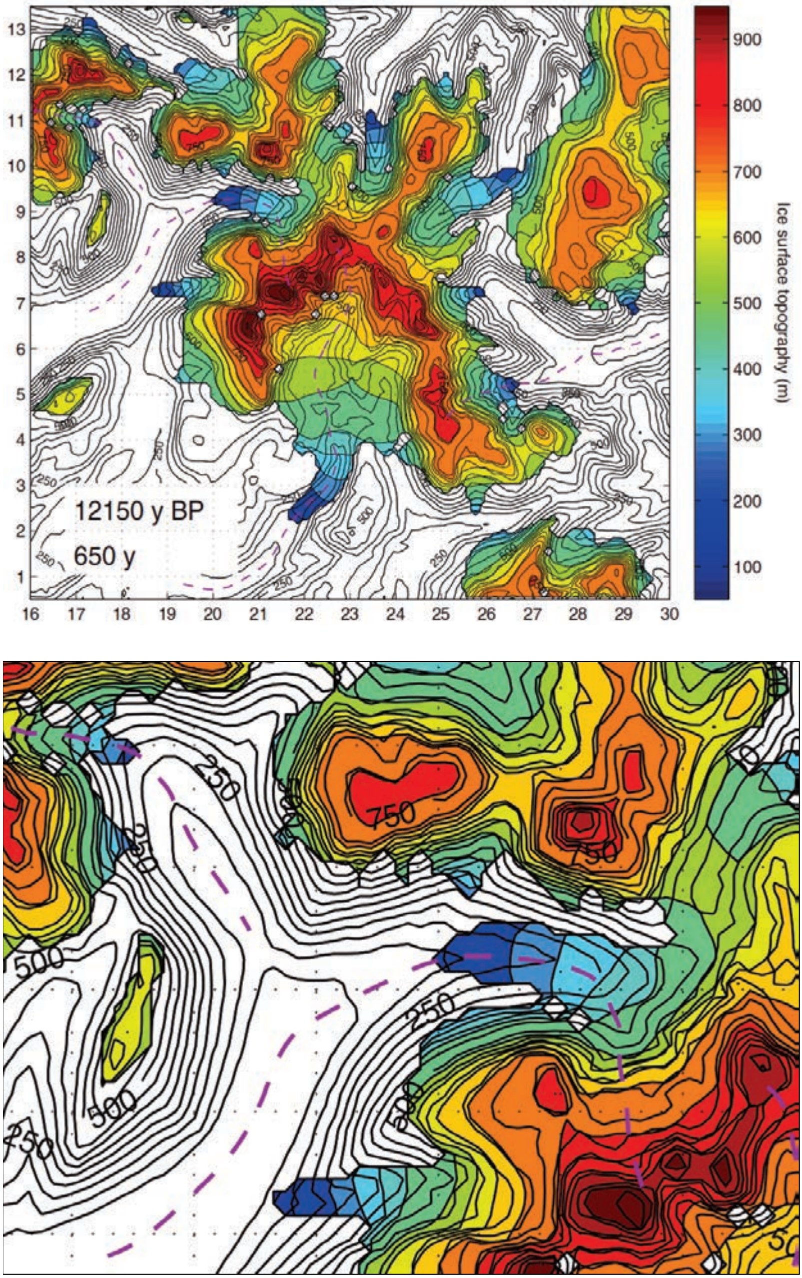


Figure 14.15. The 12,150 yr BP time slice from the numerical model, showing the ice surface topography (coloured contours) and bed topography. This represents the medium extent position of the icefield margins but also the margin of the most prolonged duration. Upper image shows the whole icefield and lower image is an enlargement of Wasdale Head.

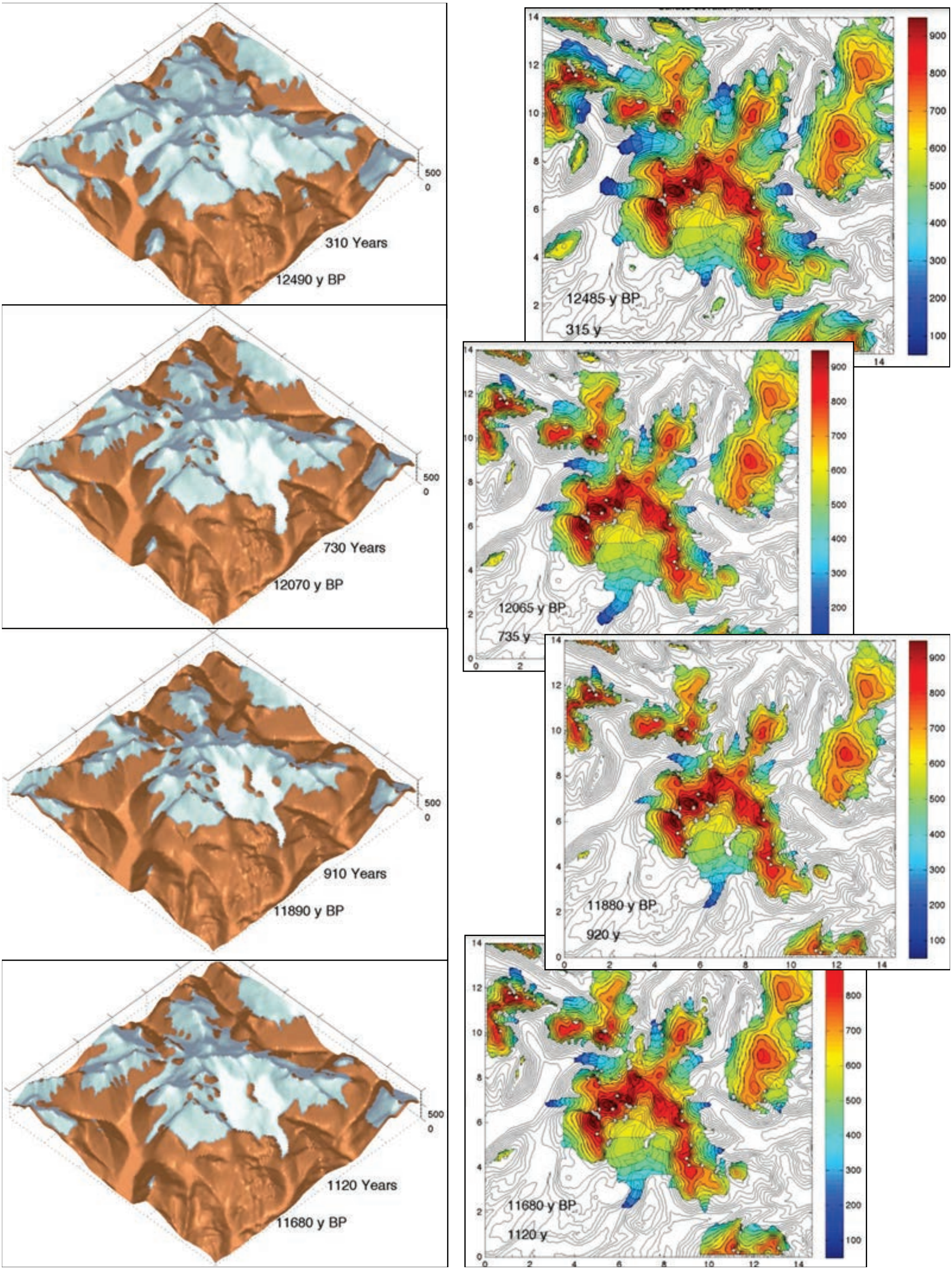


Figure 14.16. Selected time slices from the numerical model of plateau icefield style glaciation.

The reconstruction derived from numerical modelling (Figure 14.15) produces glacier extents during the Younger Dryas that are consistent with the majority of the geomorphological features (moraines) and ELAs that fluctuate between 450 and 680 m OD (mean Younger Dryas cold phase ELA of 580 m). Unlike the static (steady state) morphostratigraphically based reconstructions, the time-dependent numerical model produces two or three major re-advance positions rather than one, a palaeoglaciological history that is recorded in the moraine record. The earliest and most extensive advance was of relatively short duration and was a response to an initial significantly colder climate (mean ELA of 499 m OD for the relevant 200-year period). The less extensive second and third re-advances are of much longer duration and relate to periods of higher ELA (means of 585 and 575 m OD respectively). In Mosedale and Lingmell Beck these readvances overlap. Figure 14.15 depicts the model output for the 12,150 yrs BP time slice (650 years model time), the second re-advance phase, matching well with the most prominent latero-frontal moraines in Mosedale, Lingmell Beck and Lingmell Gill. Most significantly, the Mosedale Younger Dryas maximum ice limit coincides with the Black Comb latero-frontal moraine arc and agrees with the reconstructions of both Manley (1959) and Sissons (1980). Another interesting output from the model is the production of a substantial ice body in the bedrock gulley on the west summit edge of Kirk Fell, indicating that the Younger Dryas was the prime time to feed snow/slush avalanches into Mosedale and hence construct the snow avalanche impact pit. Figure 14.16 shows various time slices from the numerical model and illustrates the oscillatory and time transgressive nature of the dynamics of the various outlet glacier lobes.

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